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CONTRIBUTIONS TO EXPLOSIVE ECHO RANGING (U)

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UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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CONTRIBUTIONS TO EXPLOSIVE ECHO RANGING

Prepared by:
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ABSTRACT: This report presents a number of short contributions to the subject of explosive echo ranging. The subjects treated are the sonar equations for transient sources, the spectrum of repeated explosions, echo-to-reverberation ratios in EER, depth settings for EER charges, the reverberation problem in deep JULIE, and the minimum explosive source levels required in EER.

U. S. NAVAL ORDNANCE LABORATORY
White Oak, Silver Spring, Maryland

30 November 1961

During recent studies of the broad subject of explosive echo ranging (EER), a number of individual problems have arisen. These problems have varied from the general one of the form of sonar equation to use in prediction for short transient sound sources, to the specific one of the characteristics of the energy spectrum of a series of explosive pulses, and have included such practical matters as the best depth for exploding the charge in deep-water EER. The present report is a compilation of a number of such short studies aimed at clarifying some of the puzzling problems peculiar to EER. The work was done under WepTask RUDC-2B-000/212-1/F001-13-002, EER Research, and will be of interest to those concerned with explosive echo ranging or the underwater propagation of explosive pulses.

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Captain, USN
Commander

Z. I. SLAWSKY
By direction

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CONTENTS (CONT.)

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I

THE SONAR EQUATIONS FOR SHORT TRANSIENTS*

1. This is a report on a new form of the sonar equations applicable for prediction purposes to EER. They are also useful for transients like a decaying sinusoid or a pulse of irregular envelope, and are an extension of the ordinary sonar equations now widely used for performance prediction in systems analysis and design.

2. The customary sonar equations appear in Table I. Here I_o is the outgoing intensity level at one yard from the source on its axis; $(TL)_E$ is the transmission losses for the echo, with spherical divergence without absorption assumed for the reverberation; DT_N and DT_R are the threshold signal-to-background ratios for noise and reverberation; V and A are the reverberating volume and area, respectively; Ψ and Φ are the ideal solid-angle and plane-angle beamwidths of the source-receiver combination. t_o is the pulselength produced by the source. Other symbols have their normal significance.

3. These equations are in intensity units. They imply (1) that the mean intensity is constant over the duration t_o of the pulse and (2) that steady-state state conditions exist. The second condition means that the transmission loss is that applying to CW, such that all paths to and from the target have time enough to contribute to the intensity of the echo.

4. These conditions do not apply for transient underwater sounds like the short spike produced by an explosive. Here the mean intensity, or average rate of power flow is definable only in a mathematical sense. Moreover, this mathematical definition of I and t_o applies only close to the source, where the exponential form $P = P_o e^{-t/t_o}$ is followed. At longer range, distortion of pulse shape occurs due to multiple paths and absorption, and the intensity, averaged over the duration of the pulse, is made ambiguous by the effects of the medium and the target.

5. These considerations require us to have another look at the equation when dealing with transients of indefinite waveform. Obviously we must seek a redefinition based on <u>energy</u> rather than on <u>rate</u> of energy flow. The reason for this is that the energy of a sound wave may be suspected to be a conservative

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*Paper presented at the November 1961 meeting of the Acoustical Society of America, Cincinnati, Ohio.

TABLE I

INTENSITY FORM OF THE SONAR EQUATIONS

Noise Background

$$I_o - 2(TL)_E + T = N + DT_N - DI_N$$

Reverberation Background

$$I_o - 2(TL)_E + T = RL + DT_R - DI_R$$

Volume Rev

$$\begin{cases} RL_v = I_o - 40 \log r + S_v + 10 \log V \\ V = (\psi r^2 \frac{ct_o}{2}) \end{cases}$$

Surface Rev

$$\begin{cases} RL_s = I_o - 40 \log r + S_s + 10 \log A \\ A = (\Phi r \frac{ct_o}{2}) \end{cases}$$

quantity to which we can apply the ordinary steady-state transmission loss; absorption may be applied to it directly in its ordinary sense of a coefficient, without complications. While the mean intensity of a transient like a decaying sinusoid, can be stated only in a mathematical way, and is affected by propagation in a complicated way, the total acoustic energy radiated by the source is usually defined, and follows simple conservation laws when propagated in the sea.

6. In seeking a formulation on an energy basis, one must pause to consider what is being implied in the sonar equations. On the left side of the equality is the intensity or energy of echo; on the right is the background which just masks the echo. In the intensity form, the equations say that the (intensity) level of the echo is equal to the (intensity) level of the background which just masks it. As an equality of energy, the expressions must state that the energy of the echo equals the energy of the masking background. This latter energy must be the energy of the masking background <u>taken over the duration of the echo</u>. Hence we have the equality:

<u>Echo Energy</u> = <u>Masking Background Intensity</u> x <u>Echo Duration</u>

This equality is a concise statement of the sonar equations in terms of energy. If we expand both sides of the equality in symbols, we get

Noise Case:

$$E_o - 2(TL)_E + T = N + 10 \log t_e + DT_N - DI_N$$

Reverberation Case:

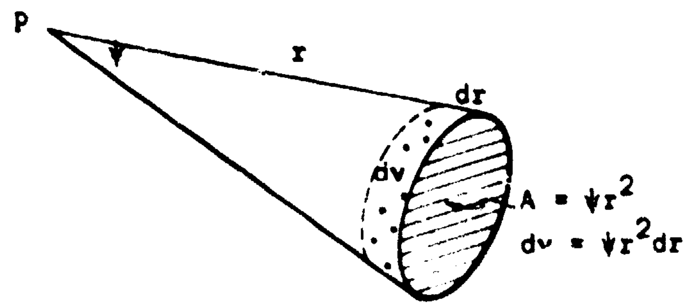
$$E_o - 2(TL)_E + T = RL + 10 \log t_e + DT_R - DI_R$$

Here E_o is the axial source energy level at unit distance; $(TL)_E$ is the ordinary long-pulse steady-state transmission loss for the echo; T is the ordinary long-pulse steady-state target strength, t_e is the echo duration; N and RL are the noise and reverberation (intensity) levels; DT_N and DT_R are the ordinary signal-to-noise ratios as required for the function that is being considered (detection, classification, etc.); DI_N and DI_R are the directivity indices against the prevailing background of noise or reverberation.

7. For transient underwater sounds, the reverberation level RL requires further consideration. In the steady-state (intensity) case, the reverberation is conceived to arise from a reverberating volume or area defined by the beamwidth and range (Ψr^2 or Φr) and the emitted pulselength ($\frac{ct_o}{2}$). In the transient

case, where no clear pulselength exists, we must make a new approach to reverberation in order to find the appropriate extension in range of the reverberating volume or area.

8. Consider volume reverberation. A transducer at P emitting a short transient receives at some later instant the reverberation coming from a small volume dV located at range r, as shown below:



Let us assume that straight-line propagation with no absorption applies. The intensity of reverberation di_r, measured at one yard from the scattering volume dV, is related to the intensity i_i incident upon it by

$$di_r = s_v \cdot i_i \cdot dV,$$

where the scattering strength S_v is related to the proportionality constant s_v by $S_v = 10 \log s_v$.

But $dV = A \cdot dr = \psi r^2 dt = \psi r^2 \cdot \frac{c\,dt}{2}$,

where dt is an infinitesimal time interval of the incident transient wave. The instantaneous reverberation intensity back at the source is

$$i_r = \frac{1}{r^4} s_v \psi r^2 \frac{c}{2} \int i_o dt$$

where i_o is the instantaneous intensity of the emitted transient measured at the reference distance. But the integral $\int i_o dt$ is the energy of the emitted transient, so that, on converting to decibel units, we obtain

$$RL_v = E_o + S_v - 40 \log r + 10 \log (\psi r^2 \frac{c}{2})$$

where 40 log r is the transmission loss for reverberation under the assumption of straight-line paths without absorption.

9. In essentially the same manner, we may obtain an expression for the reverberation from the sea surface or bottom. This

similar expression is

$$RL_s = E_0 + S_s - 40 \log r + 10 \log (\Phi r \frac{c}{2})$$

With these expressions in hand, we can now write an expanded statement of the energy equations similar to that of Table I. This statement is given in Table II.

10. A comparison of the two sets of equations indicates that they are identical except for the appearance of E_0 instead of I_0, and for the appearance of 10 log t_e on the right-hand side of the energy equations. The reverberating volume and area becomes defined by t_e instead of t_0; the extension in range of the reverberating volume or area is thus defined by the duration of the echo instead of the outgoing pulse.

11. If the quantity 10 log t_e is transposed to the left-hand side the energy equations become intensity equations in terms of the mean intensity of the echo on the left, and with the reverberation or noise intensity on the right. In this latter form, the relationships are perhaps more useful and meaningful because we are accustomed, in acoustics, to deal with intensity (in terms of the intensity of a sine wave of some reference r.m.s. pressure) rather than with energy.

12. Some consideration should be given to the important quantity, t_e, echo duration. This appears as a separate sonar parameter in the energy equations; also, it occurs implicitly in the term DT, because it is the time available for signal processing. This parameter is determined in part by the time duration of the emitted transient and partly by the effects of the medium and the target in producing an extension of the duration of the emitted transient. Thus t_e can be written as the sum of three terms: $t_e = t_o + t_m + tt$ for each of the three effects involved. These are shown in Table III, together with some typical values in each of two cases. For explosive echoes in deepwater at a beam submarine aspect, t_e may be as small as, say, 10 milliseconds; for a sonar pulse in shallow water for a bow-on submarine, t_e might be as large as 300 milliseconds. These are by no means extremes, but merely indicate the extent to which this parameter may vary. For short transients, t_e is determined by the effects of the medium and the target; for long pulse sonar, t_e is often merely the duration t_o of the emitted pulse. In this case we can write $E_o = I_o + 10 \log t_o$ and $t_e = t_o$, and the energy equations of Table II revert to the intensity equations of Table I.

13. The quantity E_o is the source energy density level measured at one yard, and expressed in decibels relative to some energy density reference. In analogy with intensity, which is referred

TABLE II

ENERGY FORM OF THE SONAR EQUATIONS

Noise Case

$$E_o - 2(TL)_E + T = NE + DT_N - DI_N$$

$NE = N_o + 10 \log t_e$ = Noise energy for the duration of the echo.

Reverberation Case

$$E_o - 2(TL)_E + T = RE + DT_R - DI_R$$

Volume $\left\{ \begin{array}{l} RE_v = E_o - 40 \log r + S_v + 10 \log V \\ V = (\psi r^2 \frac{ct_e}{2}) \end{array} \right.$ = Reverberation energy for the duration of the echo.

Surface $\left\{ \begin{array}{l} RE_s = E_o - 40 \log r + S_v + 10 \log A \\ A = \Phi r \frac{ct_e}{2} \end{array} \right.$ = Reverberation energy for the duration of the echo.

TABLE III

ECHO DURATION AS THE SUM OF THREE TERMS

	Typical Values, milliseconds	
t_o = duration of the emitted pulse at short ranges	Explosives:	0.1
	Sonar:	100
t_m = duration produced by multiple paths	Deep Water:	1
	Shallow Water:	100
t_t = duration produced by the target	Beam Aspect:	10
	Bow-Stern":	100

to the intensity of a 1 dyne/cm^2 plane wave, we may refer E_0 to the energy density of a 1 dyne/cm^2 plane wave for a period of one second; while its units may physically be, say, ergs per cm^2, we may avoid this by using the 1 dyne/cm^2 plane-wave reference. Also, E_0 is also expressed as energy spectrum level or energy in a 1 cps frequency band. For ordinary explosives, E_0 has been established by the work of Weston and Hersey, and is now well known.

14. Summary. In this note we have stated a form of the sonar equations that apply to EER as well as to other types of active sonars using transient waves. We have derived an energy formulation of the basic equations that reduces to the ordinary intensity formulation under steady state conditions (long pulses). It involves a new sonar parameter -- echo duration -- which depends upon the source, medium and the target and which, for long pulses, reduces to the pulselength emitted by the source. For prediction purposes, the energy form of the equations must be used whenever transients short enough to prevent the occurrence of steady state conditions are used in active sonar systems.

II

ENERGY SPECTRUM OF A SERIES OF EXPONENTIAL PULSES

1. In order to make a range computation in EER for a series of explosive pulses, we need to know the energy spectrum of a finite number n of repeated exponential pulses. This type of waveform is illustrated in Figure 1. This is the waveform of a repeated underwater spark discharge, and it is that of a number of special charge designs being explored for EER.

2. As shown in the Appendix, the energy spectrum of this time function is $\left| \frac{1}{iw + k} \cdot \frac{1 - e^{-inwT}}{1 - e^{-iwT}} \right|^2$, where $w = 2\pi f$, k is the reciprocal time constant of each member of the exponential series, and T is the interval between pulses. A diagrammatic sketch of what the energy spectrum looks like is shown in Figure 1b. It will be noted that the smooth continuous spectrum of a single pulse, shown by the dashed line in Figure 1b, is replaced, for repeated pulses, by a series of spectral peaks occurring at the repetition frequency 1/T and its harmonics, plus "satellite" peaks and nulls occurring between the main peaks. The "height" of the main peaks is (20 log n) decibels above the continuous spectrum level of a single pulse; thus, the peak power spectrum level of a series of 10 pulses is 20 db above the level of a single one. As the number of pulses increases, the main peaks (at the repetition frequency and its harmonics) become narrower and narrower while their amplitude gets greater and greater; for an infinite n the energy spectrum is that of a single pulse plus line components of infinite height.

3. For approximate purposes it is adequate to separate the two terms in the product for the power spectrum, and write

$$\left| \frac{1}{iw + k} \cdot \frac{1 - e^{-inwT}}{1 - e^{-iwT}} \right|^2 \approx \left| \frac{1}{iw + k} \right|^2 \cdot \left| \frac{1 - e^{-inwT}}{1 - e^{-iwT}} \right|^2$$

This separation is strictly correct only when the second term is either all real or all imaginary; this is generally true at the peaks and troughs of the spectrum. If we make this separation, we see that the effect of repetition of pulses is to add, db-wise, a "correction" term to the continuous spectrum of a single pulse, given by the first term.

4. This "correction" term in decibels is plotted on the attached graphs for pulse trains of 2, 3, 4 and 10 pulses. (Figures 2 and 3)

Also, Figure 4 shows the general nature of this term for large n.

5. The practical use of a train of pulses in EER would include a narrow receiving filter band centered about the repetition frequency or about one of its harmonics. The spectral energy density at this frequency would be that for a single pulse (the Weston-Hersey curves in the case of explosive pulses) plus 20 log n. The filter band necessary to "accommodate" the main spectral peak would have a width of $\frac{2}{n} \cdot \frac{1}{T}$ cycles per second.

III

ECHO TO REVERBERATION RATIOS IN EER

1. The problem is to formulate some useful expressions for the ratio of echo level to the level of surface reverberation for explosive sound sources. The problem is important in EER systems using a deep charge and a deep hydrophone, where the sea surface is insonified at a relatively large grazing angle. Under these conditions, the back-scattered return from the surface is relatively large, and the echo from an adjacent submarine target tends to be buried in the reverberation which arises from the sea surface immediately overhead.

2. The problem of EER echo-to-reverberation ratio has recently received attention by A. D. Voorhis in an article in the Journal of Underwater Acoustics for January 1961 (reference (a)). His treatment of the problem is unnecessarily complicated. Moreover, he fails to use published measured data on the sea surface scattering coefficients, and relies instead on a mathematical description of the form of the sea surface. The answers he obtains appear to be erroneous, and are excessively optimistic as to the echo-to-reverberation ratios to be expected at long ranges.

3. We will here adopt the approach taken in NAVWEPS 7384 (reference (b)), and utilize certain back-scattering coefficients already appearing in the literature (reference (c)). It will turn out that, for submarine targets, the echo stands out above reverberation in a deep non-directional system only when the sea surface is relatively smooth - that is, for low sea states, say, sea state 1 or 2. At higher sea states, the echo will tend to be lost in the reverberation background.

4. It is shown in reference (b) (page 18) that the reverberation spectrum level from a nearly plane surface like the sea surface or sea bottom is, on the assumption of straight-line paths, and with a non-directional source and receiver,

$$RL = E_o + S_s - 30 \log r - 2\alpha r + 10 \log \pi c$$

where E_o is the spectrum level of the charge; S_s is the surface scattering strength; r is the slant range between the charge-receiver (assumed adjacent to each other) and the surface; α is an absorption coefficient, and c is the velocity of sound in units of r per unit time. Neglecting absorption (the term $2\alpha r$) and replacing $10 \log \pi c$ by 37 db (r is in yards), we have

$$RL = E_o + S_s - 30 \log r + 37$$

It is also shown in reference (b) (page 22) that the echo level is

$$EL = E_0 - 10 \log t + T - 40 \log r$$

where t is the duration of the echo and T is the target strength. The echo-to-reverberation ratio is then, in db,

$$EL - RL = T - 10 \log t - S_s - 10 \log r - 37.$$

5. For a beam aspect submarine target, we will assume T = 25 db, t = .030 sec., so that T - 10 log t = 25 + 15 = 40 db. At the other extreme, we will take a bow-stern aspect submarine having values of T and t that approach the beam-aspect case as the target approaches the zenith-point over the charge-hydrophone. For the bow-stern aspect target, we will adopt the following values:

Grazing Angle	T	t
15°	12 db	.10 sec
30°	14	.08
45°	16	.07
60°	18	.06
75°	20	.05

6. The quantity S_s has been measured at kilocycle frequencies in connection with torpedo homing applications. Values at 60 kc have been published (reference (c)); unfortunately, there is no data at lower frequencies.* The 60 kc coefficients show no falling off with decreasing grazing angle below about 30° in moderate and high sea states. This is a peculiarity attributed to a layer of air bubbles just below the surface. Values of S_s as read from curves in reference (c) are used in the following computations.

7. Using these values, and with the above assumptions of T and t, curves of EL-RL are given in Figures 5 and 6 for the beam aspect and the bow-stern aspect situation.

8. Figure 5 indicates that, for a source-receiver at a depth of 12,000 feet, a beam-aspect target lying beyond 4000 yards will produce an echo just equal to the surface reverberation (EL=RL) at a wind speed of 11 knots. Inside of this range the echo will be rapidly lost in surface reverberation. Similarly, Figure 6 indicates that a bow-stern aspect target will be obscured in reverberation when the wind speed exceeds about 6 knots. The steeply sloping lines in Figure 5 are the echo-to-reverberation ratios predicted by Voorhis in reference (a).

*In the work of reference (c) essentially identical values were found at 25 kc as at 60 kc.

9. However, an EER echo will be detected when its level lies below that of the reverberation. A method of predicting the detection threshold for a simple envelope detector is given in reference (d). The dashed lines in Figures 5 and 6 show the echo-to-reverberation ratio required for detection for a square law detector preceded by a filter of bandwidth 2000 cps. The difference between these lines and zero is the detection threshold. For the bow-stern aspect case, the line slopes slightly to the right, reflecting the fact that the echo duration t and therefore the detection threshold change with range. The maximum tolerable wind speed for target detection is 14 knots for beam aspects, and 9 knots bow-stern aspects, at horizontal ranges between 4000 and 12,000 yards.

10. These predictions were made on the basis of 60 kc scattering data. At lower frequencies somewhat better performance should be had because the sea surface is probably a poorer backscatterer of sound at lower frequencies. How much smaller the coefficients are at lower frequencies is a matter requiring field measurement.

IV

THE REVERBERATION PROBLEM IN DEEP JULIE

1. In the Deep JULIE System, the charge and the sonobuoy hydrophones are placed at depths near 12,000 feet, so as to take advantage of the so-called Reliable Acoustic Path between a deep transducer and a near-surface target. Ray diagrams show that a near-surface target will lie in the direct sound field of the source out to ranges of 30,000 yards or more, and that there will be a direct path between source and target, and return, out to long ranges. Unfortunately, however, there is also a direct path to and from the near-surface scatterers in the vicinity of the target; these scatterers give rise to the background of reverberation in which the target echo must be detected. This reverberation background arises from, or near, the sea surface at the same range as the target, and can be discriminated against only by incorporating horizontal directionality into the system.

2. This background is identical in nature to that which is troublesome in acoustic mine-hunting for bottom mines, and in the radar detection of snorkel heads and periscopes. In these applications extreme directivity in the horizontal plane is required in order to reduce the background of clutter surrounding the echo. But, in addition, the deep JULIE system is also hindered by the presence of sea bottom, which along with the surface, gives rise to reverberation occurring along near vertical paths; such reverberation can be relatively easily reduced by vertical directivity in the source or hydrophone or (probably) both.

3. Our problem is concerned with estimating the magnitude, relative to the echo, of the first form of reverberation. If the near-vertical background can be reduced to insignificance by the use of a line hydrophone and charge, will the remaining reverberation prevent detection of the echo? If so, the only recourse for further appreciable system improvement is to incorporate multiple preformed beams in the horizontal plane, with their required hydrophone and electronic complexities.

4. The nature of the problem may best be appreciated through Figure 7. This shows diagramatically the reverberation observed with a non-directional charge and hydrophone near the deep sea bed. Field tests have shown that submarine targets are detectable only with difficulty with this non-directional system. The reverberation background consists of repeated bottom-surface scattered returns A, A', A" etc. which obscure a long-range target, but which can be taken care of through the use of a

reasonable amount of vertical directionality in the explosive source and the hydrophone. However, there will still remain the direct-path surface reverberation, A-B, that cannot be reduced relative to the echo by vertical directionality.

5. In Section III a method was given for predicting the level of this reverberation background relative to the echo, based upon computations using surface scattering coefficients measured at 25 and 60 kc. The results indicated that, even if the near vertical returns are removed completely, the remaining direct-path surface reverberation will prevent echo detection in all but calm seas.

6. This conclusion is questionable because of the use of 25-60 kc data for a system operating near 2 kc. Recently, new measurements of low frequency sea-surface scattering coefficients by R. P. Chapman at Naval Research Establishment, Halifax have come to light.* The data for three wind speeds at the frequencies of direct interest to Deep JULIE are summarized in Figure 8 for the two octaves 800-1600 cps and 1600-3200 cps.

7. With these coefficients, the predicted echo-to-reverberation ratios are plotted in Figure 9 for beam-on and end-on target aspects. The detection limit given in these figures is that of the optimum detector and a well trained alert observer, at the 50% detection level with 5% false alarms. From Figure 9 it will be seen that beam aspect submarines should be detectable by the optimum detector-observer combination at all wind speeds up to about 30 knots at ranges beyond about 6000 yds. A bow-stern target should be detected at wind speeds only up to 12 knots. If we allow 5 db for the failure to realize the optimum detector and observer, the corresponding wind speed limits of detectability become 20-25 knots and 7-10 knots for the two cases.

8. In order to see what this means in terms of the wind speeds occurring in the North Atlantic, the distribution of wind speeds averaged over all seasons of the year for the Atlantic Ocean between latitudes 40°N and 60°N, together with data for the months of February and August, is plotted in the upper part of Figure 10. These curves were derived from data in reference (e). Combining the distribution curve for all seasons of the year with the range prediction curves of the previous figure, we obtain curves of percentage of targets detectable against the direct-path surface reverberation background. These curves are plotted in the lower part of Figure 10.

*A paper on the subject "Surface Reverberation from Explosive Sound Sources" was presented at the 19th Symposium on Underwater Acoustics, November 1961.

9. The results of this analysis may be summarized as follows:

a. If sufficient vertical directivity is incorporated in Deep JULIE to reduce the near-vertical bottom-surface return to insignificance, then submarines will be detected in the North Atlantic at horizontal ranges beyond 10,000 yards between 10% and about 70% of the time, depending on target aspect. This estimate of range performance applies only if (1) the bottom-surface bounces are completely eliminated and (2) ambient or other noise sources are made negligible. A random-aspect target at a given range should be detected a fraction of the time about half-way between the two limiting curves of Figure 10.

b. Further improvement will require horizontal directionality. Ten 36° beams would improve the echo-to-reverberation ratio by 10 db, and raise the detection percentages to essentially 100% for beam targets and to 50-70% for end-on targets beyond 8000 yds.

c. Target detectability becomes worse at shorter ranges because of the increased return from the sea surface immediately over the charge-hydrophone.

d. Target detectability improves with range out to extreme ranges, in spite of the fact that increasing areas of surface act to send back reverberation as the range is increased. This is due to the fact that the back-scattering coefficient of the sea surface, according to the new data, falls rapidly as the grazing angle is diminished. At extreme ranges ambient noise may well become the dominant background, but can be overcome by increasing the charge size.

10. These predictions are based on yet-unpublished surface scattering coefficients. Verification is required from additional scattering coefficient measurements now being obtained by the Martin Company and Daystrom, Incorporated, and from field results with vertically directional Deep JULIE equipment.

V

DEPTH SETTINGS FOR EER CHARGES

1. The problem to be considered is that of the optimum charge depth for JULIE detection in deep water. In particular, it is addressed to the problem of how to choose, from a sound transmission standpoint, between charge depths of 60, 300 and 800 feet, and to the conditions of layer depth and target depth under which each depth is optimum. This problem is of current interest in connection with proposed modifications of charge depth settings, and with the formulation of operational doctrine concerning the selection of charge and sonobuoy depths for JULIE.

2. The problem may be stated in the following way: given a knowledge of sound transmission conditions - in particular, layer depth and sea state - and a guess as to the likely depth of the target as being above or below the layer, is a charge depth of 60 feet, 300 or 800 feet preferable in terms of best sound transmission conditions?

3. This question can be answered by means of the computer synopsis of the AMOS sound transmission data of reference (f), in which the transmission loss is given as a function of range for various frequencies, source depths, receiver depths, and layer depths, based upon the well-known AMOS program of about ten years ago. This data is, at the present time, the best available source of transmission loss information for the conditions to which it applies. From reference (f), at a frequency of 2 kc, the range at which the transmission loss is 80 db was read off for various combinations of source, target and layer depths.

4. The results are shown in Figure 11. The upper portion of this figure shows range (for 80 db loss) plotted against layer depth for source depths of 60, 300 and 800 feet. The target was assumed alerted, and therefore to lie below the layer between the depth limits of 50 and 375 feet; the target depth assumed for each plotted point is shown alongside the horizontal scale. The lower part of the figure is similar, except that the target is unalerted and is assumed to be at a depth of 50 feet.

5. From Figure 11, the following conclusions may be drawn:

a. For an alerted target hiding below the layer, the 800 foot source is always preferable to one at 60 or 300 feet. The improvement in range will be substantial if a thin layer exists, but will be less marked for layers greater than 100 feet in thickness.

b. For an unalerted (e.g. snorkelling) target at a depth of 50 feet, the 800 foot charge will continue to be preferable as long as the layer is less than 100 feet in thickness. But for thicker layers, the shallow (60 ft) charge will be preferable although under these conditions its advantage in transmission loss may be counter balanced by increased reverberation. The 800 foot source has the additional advantage of giving a range performance nearly independent of layer depth and target depth; the range for an 80 db transmission loss lies between 5000 and 7000 yards for all conditions considered here.

6. The next step is to consider the occurrence of layer depths in the open ocean. A study of layer depth occurrence in the North Atlantic between latitudes 40N and 60N indicates that layers less than 100 feet thick occur 34% of the time on a year-round basis; 100 to 400 feet layers occur 59% of the time; layers greater than 400 feet in thickness occur 7% of the time. For these three groups of layer depths, Table IV shows the preferred charge depth (as between 60, 300 and 800 feet) for an unalerted and an alerted target.

7. A strong word of caution is necessary. The above conclusions are based on AMOS transmission data for sea states less than 3; such calm seas hardly prevail in the North Atlantic. However, high sea states are normally associated with thick mixed layers, and their effect on sound transmission should be small out to JULIE ranges. A more serious restriction is that we have not considered reverberation as a function of source depth, since reverberation data of this kind is lacking. Sinking times have not been considered. All these factors would have to be considered in a complete analysis. Thus, the conclusions arrived at here are meant to be merely suggestive, and are based upon only one of the factors on which echo duration depends.

8. Within the limitations suggested in the preceding paragraph, the following recommendations are made:

(1) Replace the 300 foot charge setting by 800 feet, if the increased sinking time is permissible.

(2) Retain 60 feet for use against an unalerted target when the mixed layer is 150 feet or more in thickness.

(3) Obtain quantitative data on a calibrated db basis to check these recommendations, which are based on calm-sea transmission data alone. Reverberation data is particularly needed for various source depths, and echo and reverberation data is needed in rough seas.

TABLE IV

BEST CHOICE OF SOURCE DEPTH FOR
SOUND TRANSMISSION TO AN UNALERTED
AND ALERTED SUBMARINE

Layer	Percentage Occurrence in N. Atlantic, Lats 40-60N	Target Unalerted (50 ft)	Target Alerted (below layer)
Thin (less than 100 ft)	34%	800 ft	800 ft
Medium (100 ft to 400 ft)	59%	60 ft	800 ft or 60 ft *
Thick (greater than 400 ft)	7%	60 ft	60 ft **

* Little difference between the two.

** Target cannot go appreciably below layer because of depth restriction.

VI

EXPLOSIVE SOURCE LEVELS REQUIRED FOR EXPLOSIVE ECHO RANGING

1. As replacements for, and improvements upon, the customary TNT-type explosives employed in EER, various new and novel sound sources have been, and are being investigated. These unusual sound sources, such as the underwater spark, are usually aimed at overcoming the principal drawback of explosive charges: repeatability. However, in so doing, it has been suspected that they will fall far short of what is needed, energy-wise, for EER detection, and that they would be too weak to provide a detectable EER echo if used in the field against a submarine target.

2. This short report presents a method for finding this minimum energy level required for an effective EER source. A curve will be given for this minimum level as a function of range, and the levels of a number of experimental sources, as well as TNT charges, will be compared with these minimum levels.

3. The starting point is the generalized sonar equation in terms of the acoustic energy of the source. This equation is

$$E_o - 10 \log t + T - 2H = N + DT - DI$$

This equality states that the average intensity of the echo, given on the left, equals the masking level of the noise background. E_o is the energy spectrum level of the source on its axis, in db relative to that of a plane wave of pressure 1 dyne per cm^2 taken over a period of 1 second; t is the echo duration in seconds; T the long-pulse CW target strength; H is the long-pulse CW transmission loss; N, the background noise intensity level in db relative to that of a plane wave of pressure 1 dyne per cm^2; DT, the detection threshold, or signal-to-noise ratio needed for detection; and DI the directivity index of the receiving hydrophone against the prevailing noise background. An equation of identical form applies if the background is a reverberation instead of noise.

4. In computing a value for E_o, we will make the following assumptions:

a. The background in which the echo is detected is deep sea ambient noise, sea state 3. If reverberation, rather than ambient noise is limiting, the range for a given value of E_o will be less than that found for ambient noise. At 2 kc, N = -41 db.

b. The propagation conditions are excellent. Specifically, spherical spreading ($H = 20 \log r$) without absorption will be assumed. This simple assumption is always an optimistic, or favorable, one for transmission loss, except at very long ranges where ducting and convergence zone effects make their appearance, but which are of no concern to EER.

c. The other parameters have the following values:

$t = .08$ sec; $10 \log t = -11$ db
$T = +15$ db
frequency = 2kc
$DT = 5 \log \frac{d}{Wt} = -8$ db if $d = 3$, the ROC Curve parameter for 50% detection with 5% false alarms, and
$W = 2$ kc, approximately the JULIE bandwidth.
$DI = 0$, nondirectional receiving hydrophone.

5. Solving the sonar equation for E_o with the above values for the various parameters, we obtain the source level required for detection as a function of range. This curve is the lower curve shown in Figure 12, which is that for an optimum detector having the above value of detection threshold (-8 db). The upper, parallel curve is for DT = 0, allowing 8 db for observer loss and for mismatch between the integration time of the detector output averager and the echo length. This represents a more realistic view of what can be done in the field with echoes of uncertain duration.

6. The ordinate of Figure 12 is the 2 kc energy density spectrum level required for detection at a given range. For an exponential pulse of time constant t_o, this level is related to the peak pressure of the pulse by

$$E_o = 10 \log \frac{2P_o^2}{1/t_o^2 + 4\pi f^2}$$

where P_o is the peak pressure (in dynes/cm^2 at 1 yd) and f is the frequency. At 2 kc, the term $1/t_o^2$ may be neglected if $t_o > 10^{-4}$ sec; if this is the case, then E_o becomes independent of t_o. Figure 12 gives a scale of $10 \log P_o^2$ along side that for E_o for $t_o > 10^{-4}$ sec.

7. On the right hand side of Figure 12 are plotted the energy levels for various charge weights of TNT, and the pressure levels for a number of other types of sound sources for which peak pressures have been reported. The levels for TNT are based

on measurements made at 100 yards and "reduced" to 1 yard through assuming spherical spreading. The peak pressures for TNT are therefore somewhat lower than the peak pressures actually measured at 1 yard. The smaller charge sizes are plotted according to the energy spectrum level rather than according to peak pressure, so as to allow for the unknown decreasing value of t_0 (below 100 μs) for smaller charges.

8. The various sources shown on the right are plotted according to peak pressure, which is all that is usually given in the literature. In making the comparison it is assumed that these sources produce a pressure variation, with time, of exponential form, having an infinitely sharp rise followed by an exponentially decaying tail of time constant greater than 10^{-4} sec. If the rise of pressure with time is not as sharp as that from a high explosive, or if the time constant is shorter than 10^{-4} sec, the various levels will fall lower in the vertical scale of E_0*. Again, the difficulty stems from the fact that the energy density spectrum (E_0) is never reported in the literature.

9. It will be observed from the figure that, with the possible exception of the strongest spark source, (requiring a tremendous condenser bank charged to a very high voltage) the various sources listed are the equivalent, energy-wise, of no more than a tiny charge of TNT. They will not produce an EER echo at ranges greater than 2000 yds, even under the ideal conditions assumed. From this analysis we may conclude the following:

a. For EER under good-to-excellent conditions (ambient noise background, spherical sound transmission), the smallest charge of TNT (or tetryl) that will give a detectable echo out to the first bottom in deep water is about 1/10 lb (1.6 oz). Larger charge sizes will be needed under normal reverberation and transmission conditions. Smaller charges will suffice under these conditions if directivity (DI > 0) is introduced into the system. Table V gives, for convenience, the charge weights of various underwater sound signals in fleet use at the present time.

b. All novel and experimental sound sources so far developed are useless for EER in that they do not generate sufficient energy at useful frequencies (e.g. 2kc). While these sources may have naval interest for fathometry, mine sweeping, or underwater communication, they will not produce detectable EER echoes at ranges beyond about a mile.

---

*E_0 is the proper basis for range prediction, rather than peak pressure.

c. The analysis has been tacitly restricted to sources producing explosive-like acoustic waveforms. Sources which generate a quasi-sinusoidal pulse through explosive resonant excitation (of, say, a cavity) will not be appreciably better in EER performance to the initial explosive source alone, since basically the comparison of performance rests on the energy content of the echo regardless of waveform. The broad subject of obtaining a generalized figure-of-merit that will permit comparison of sources of radically different types (e.g. sonar pings vs explosions), for reverberation as well as noise background, is being studied.

TABLE V

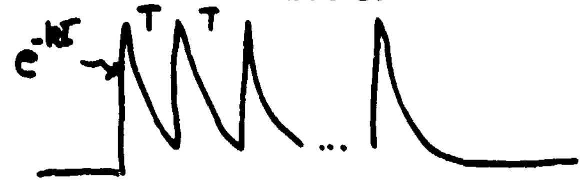
CHARGE WEIGHTS FOR VARIOUS UNDERWATER SOUND SIGNALS

Mk 15 Mod 1 (Practice)	2.0 oz Tetryl
Mk 50 Mod 0	1.8 lbs TNT*
Mk 50 Mod 1	2.9 oz Tetryl
Mk 50 Mod 2	1.1 oz Tetryl
Mk 54 Mod 0	1.8 lbs TNT*
Mk 63 Mod 0	1.1 oz Tetryl
Mk 57 Mod 0	1.8 lbs TNT*
Mk 61 Mod 0	1.8 lbs TNT*
Mk 64 Mod 0	1.1 oz Tetryl

*Signals with 1.8 lbs TNT contain, in addition, a 1.1 oz tetryl booster.

Reference: "Signals, Underwater Sound, for EER" NAVWEPS 2982, 15 Sep 1961

APPENDIX A



The general transform function is

$$f(s) = \int_0^\infty f(\tau)\, e^{-s\tau}\, d\tau$$

For a series of n pulses, each of the form $f(t) = e^{-kt}$, we have

$$f(s) = \int_0^\infty e^{-k\tau} e^{-s\tau} d\tau + \int_T^\infty e^{-k(\tau-T)} e^{-s\tau} d\tau + \dots \int_{(n-1)T}^\infty e^{-k[\tau-(n-1)T]} e^{-s\tau} d\tau$$

where T is the interval between pulses.

$$f(s) = \int_0^\infty e^{-(k+s)\tau} d\tau + \int_T^\infty e^{kT} e^{-(k+s)\tau} d\tau + \int_{2T}^\infty e^{2kT} e^{-(k+s)\tau} d\tau + \dots \int_{(n-1)T}^\infty e^{(n-1)kT} e^{-(k+s)\tau} d\tau$$

$$= \frac{1}{s+k}\left[1 + e^{kT} e^{-(k+s)T} + e^{2kT} e^{-(k+s)2T} + \dots + e^{(n-1)kT} e^{-(k+s)(n-1)T}\right]$$

$$= \frac{1}{s+k}\left[1 + e^{-sT} + e^{-2sT} + \dots + e^{-(n-1)sT}\right]$$

$$= \frac{1}{s+k}\left[\frac{1-e^{-nsT}}{1-e^{-sT}}\right]$$

Writing $s = i\omega$, and remembering that the energy spectrum

$E(\omega) = |f(i\omega)|^2$, we get

$$E(\omega) = \left|\frac{1}{i\omega + k} \cdot \frac{1-e^{-in\omega T}}{1-e^{-i\omega T}}\right|^2$$

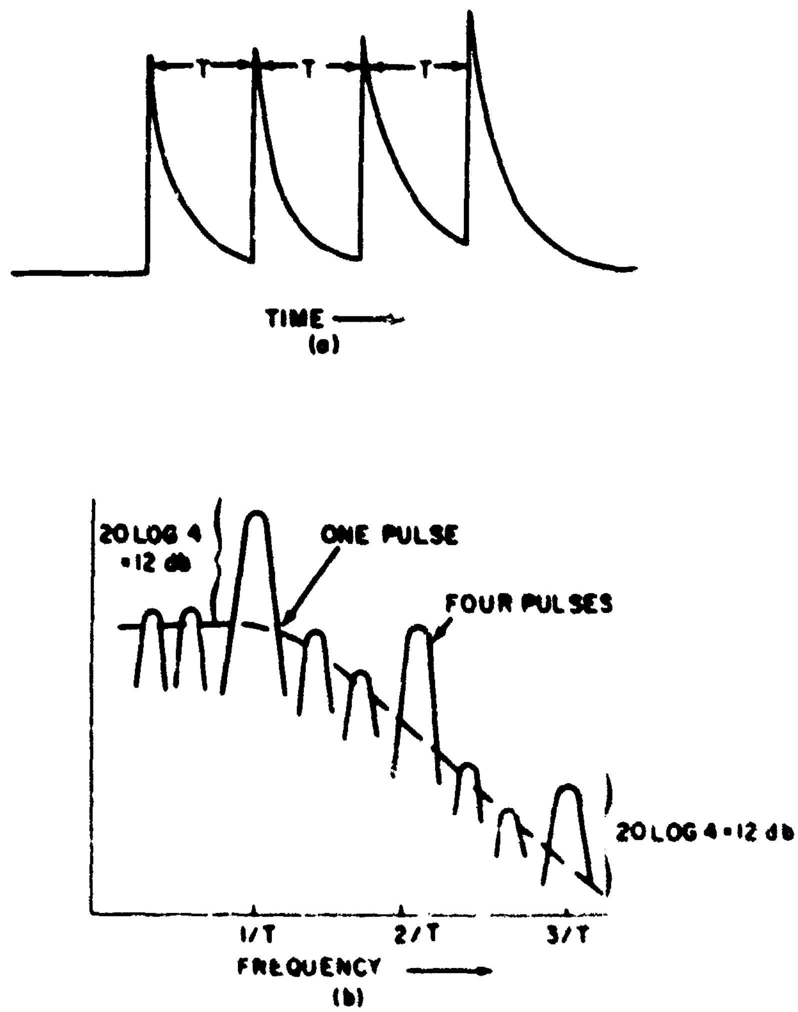

T
T
T
TIME
(a)
20 LOG 4
=12 db
ONE PULSE
FOUR PULSES
20 LOG 4 =12 db
1/T
2/T
3/T
FREQUENCY
(b)

FIG. 1

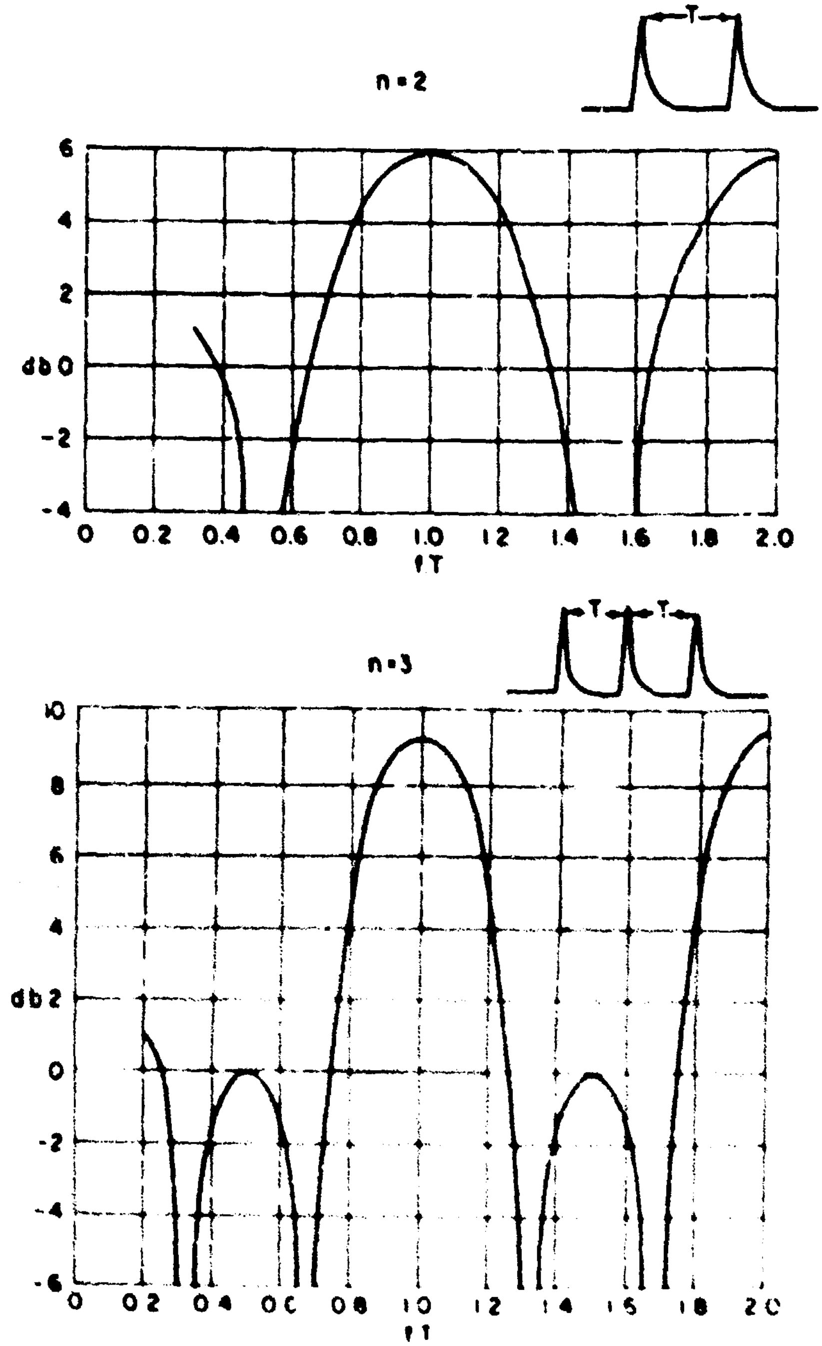

n = 2
T
6
4
2
db 0
-2
-4
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
fT
n = 3
T
10
8
6
4
db 2
0
-2
-4
-6
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
fT

FIG. 2

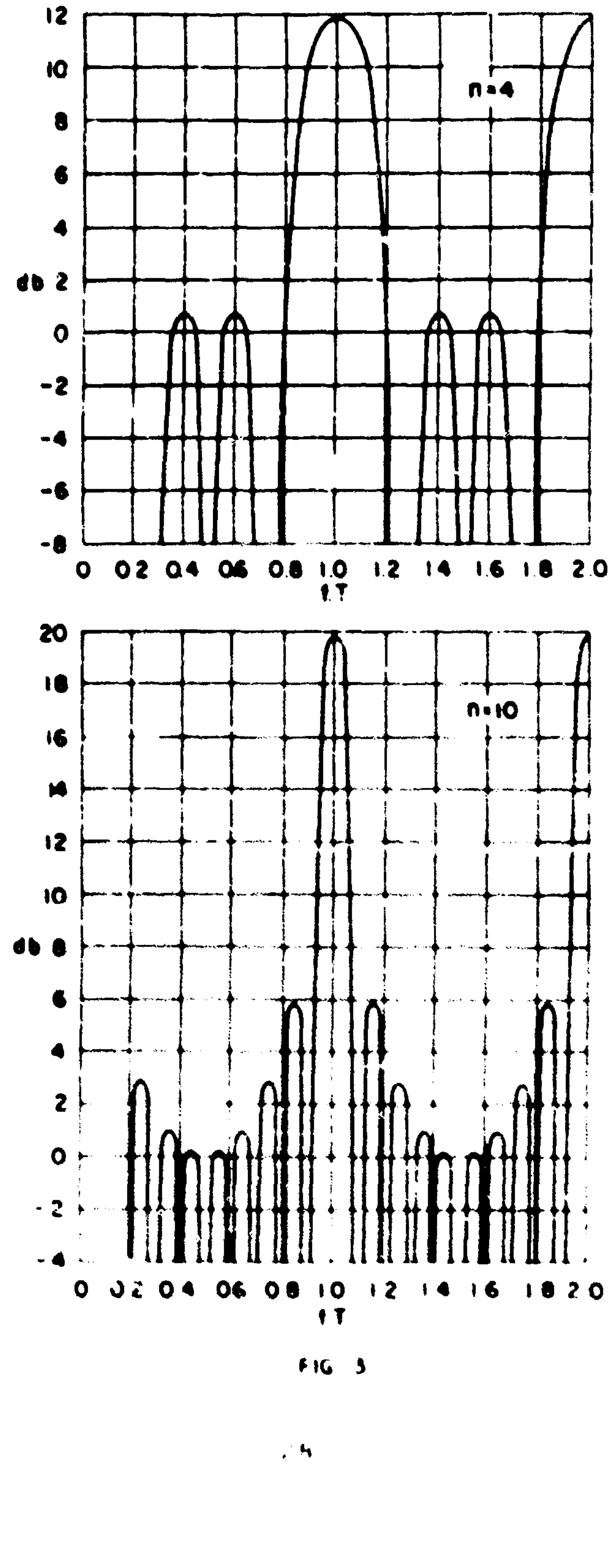

12
10
8
6
4
db 2
0
-2
-4
-6
-8
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
f T
n=4
20
18
16
14
12
10
db 8
6
4
2
0
-2
-4
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
f T
n=10

FIG. 3

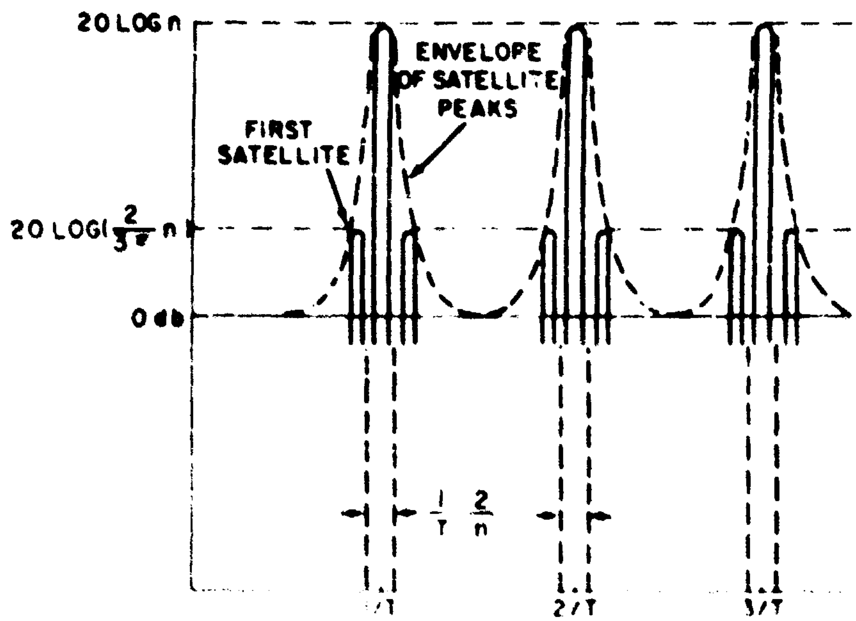


FIG 4 ENERGY SPRECTRUM FOR LARGE n

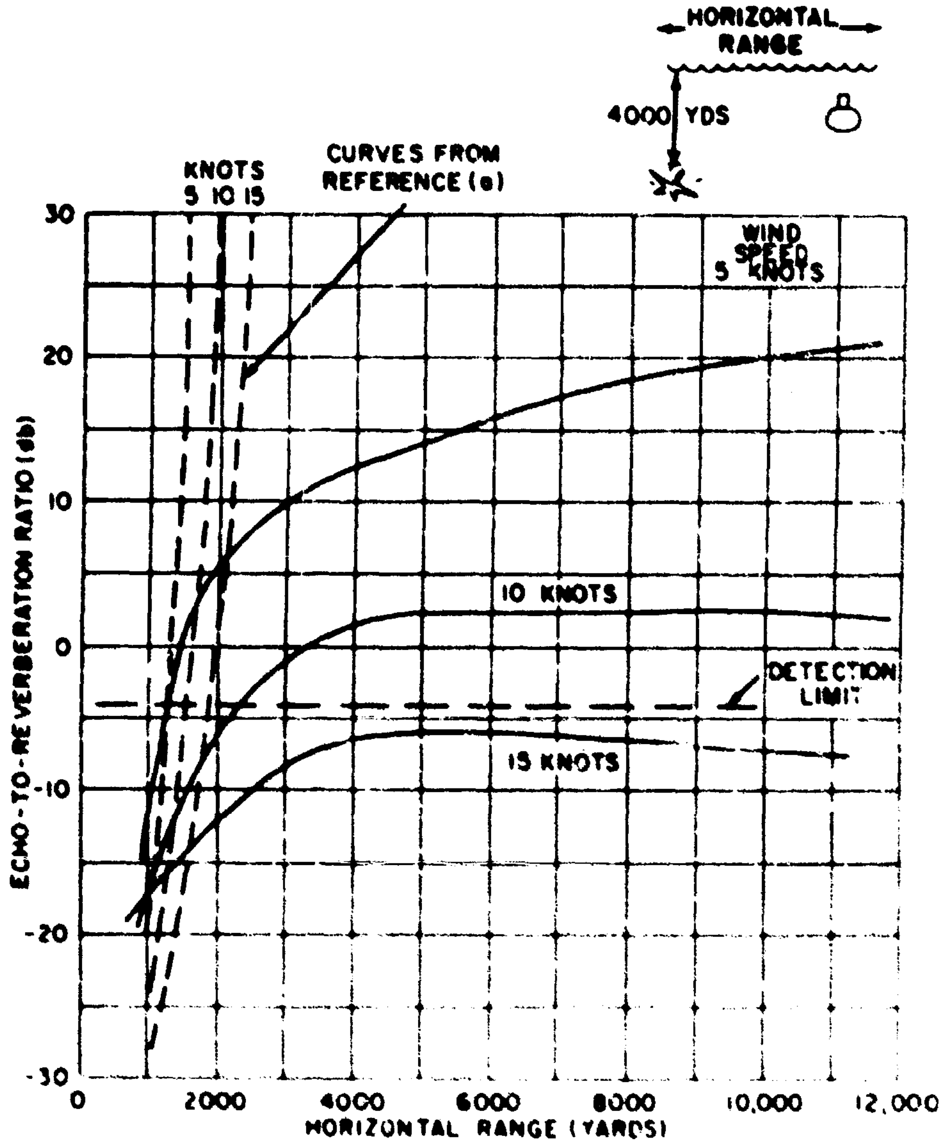


FIG 5 BEAM ASPECT TARGET
T = 25 db
T = 0.03 SECONDS

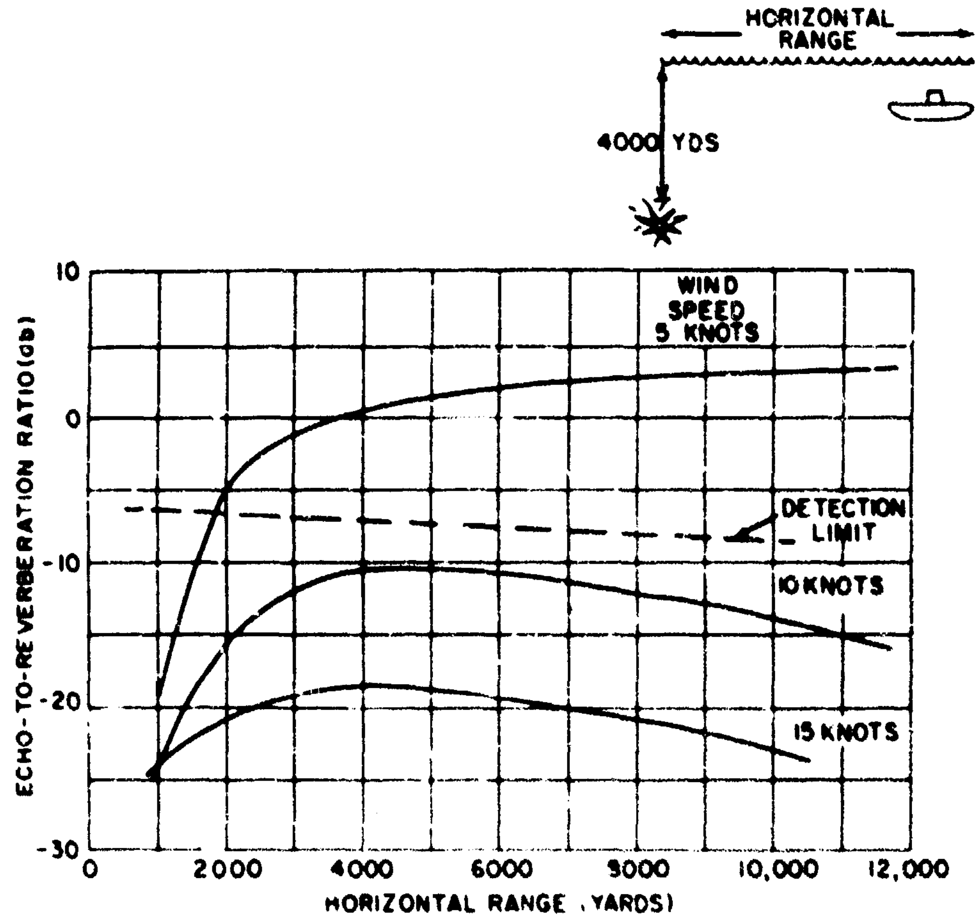


FIG. 6 BOW-STERN ASPECT TARGET
T = 12-20 db
t = 0.05 — 0.1 SEC

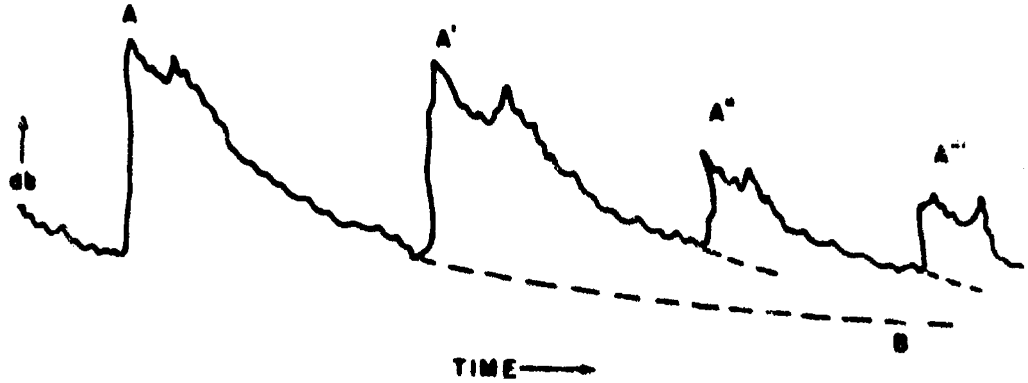


FIG 7 REVERBERATION VS TIME

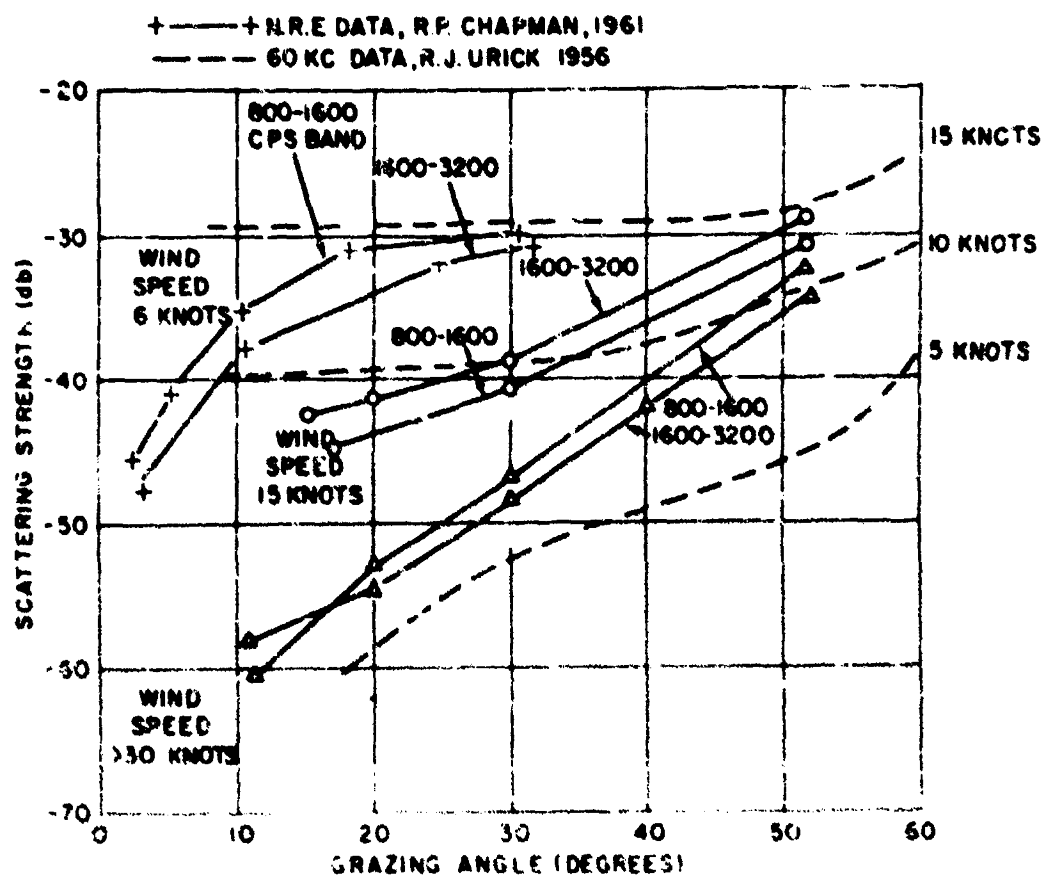
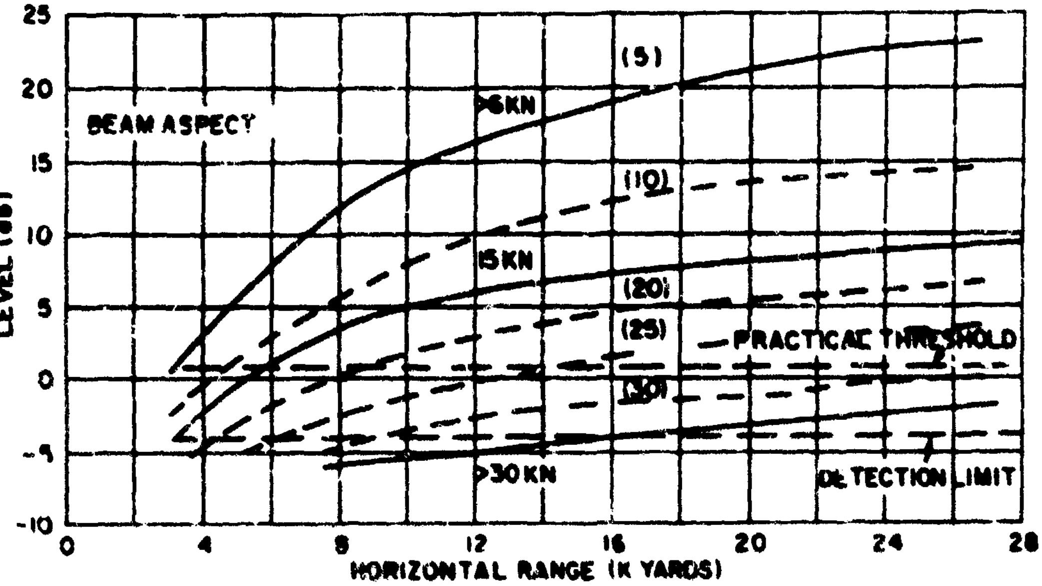


FIG 8 RECENT LOW FREQUENCY SCATTERING STRENGTHS COMPARED WITH EARLIER HIGH FREQUENCY DATA



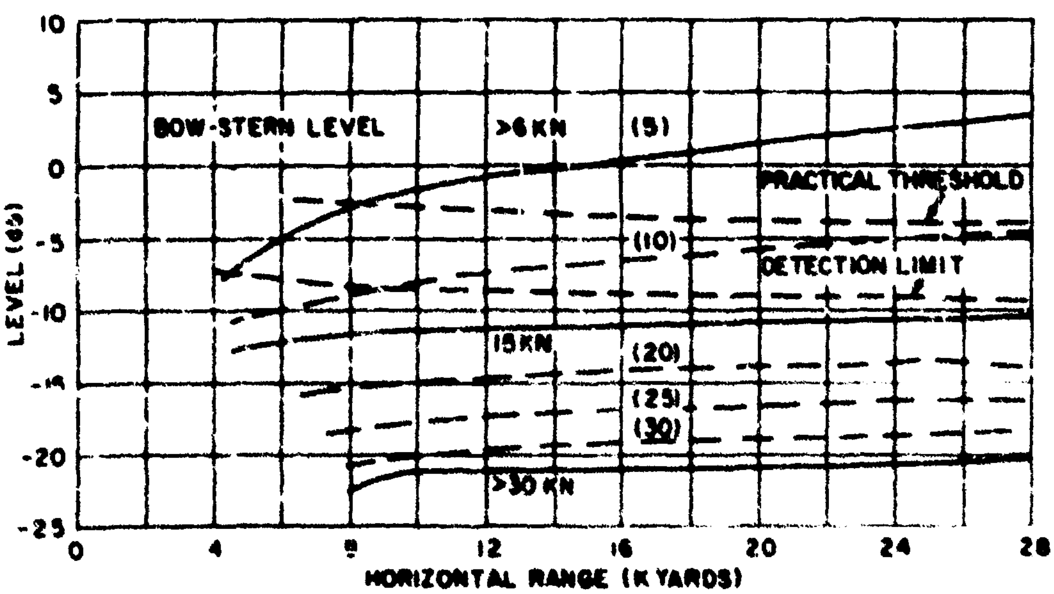
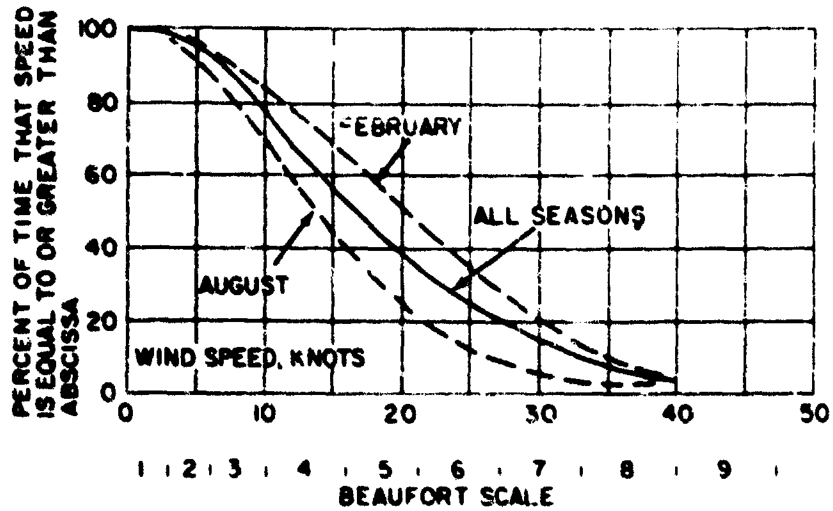


FIG. 9 ECHO/REVERBERATION VS RANGE



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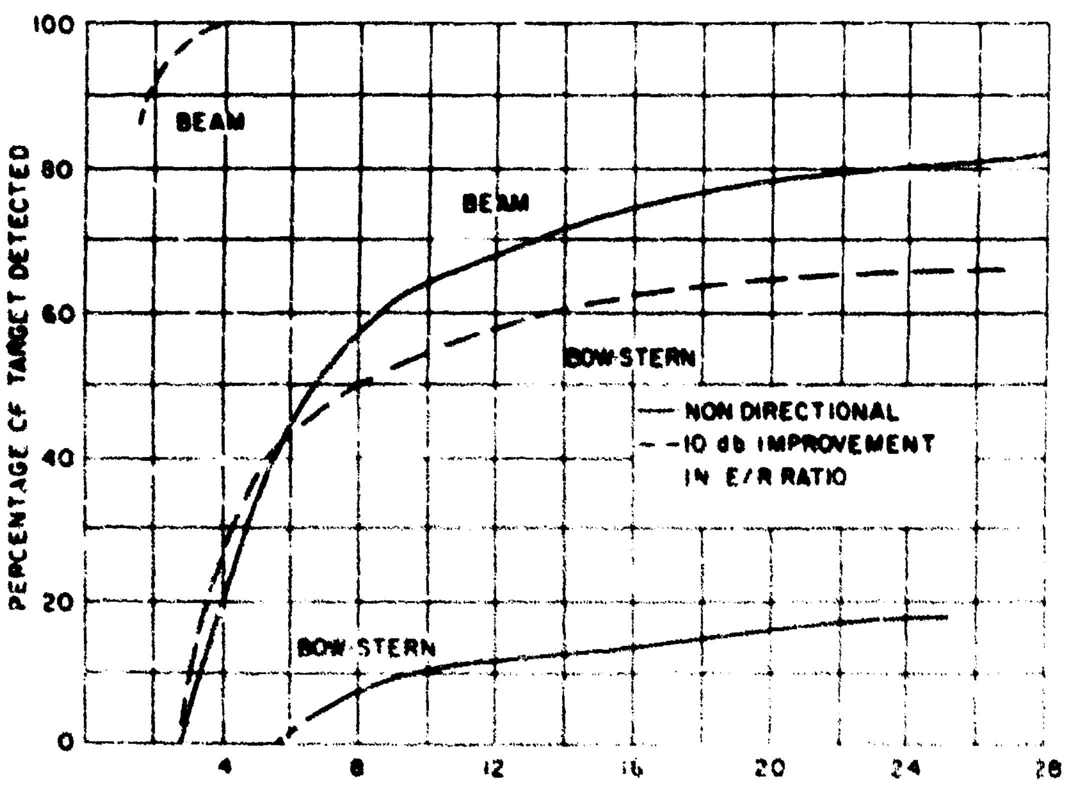
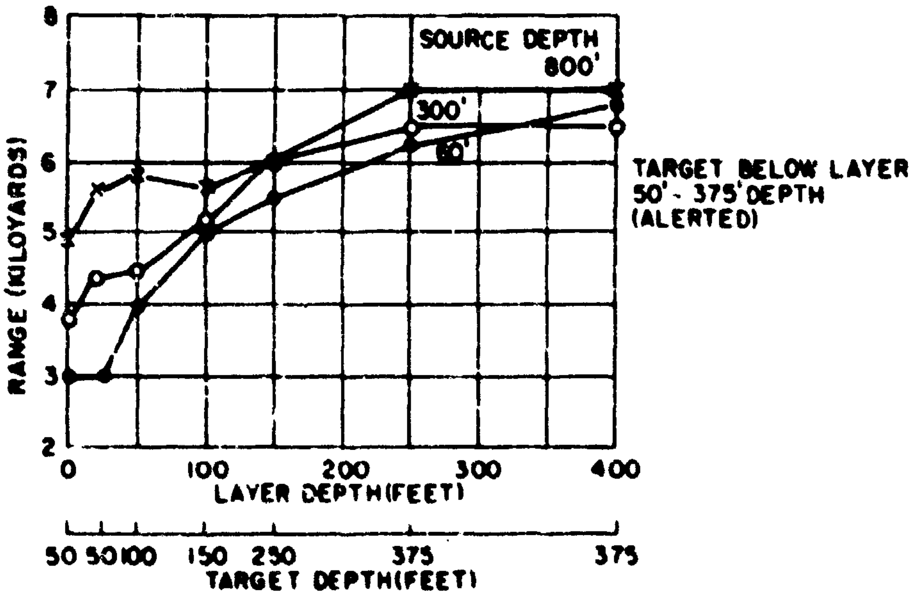


TARGET DETECTABILITY CURVES

FIG 10

SOURCE DEPTH, A PARAMETER: RECEIVER DEPTH: BELOW LAYER (UPPER FIGURE) AND AT 50 FT. (LOWER FIGURE)



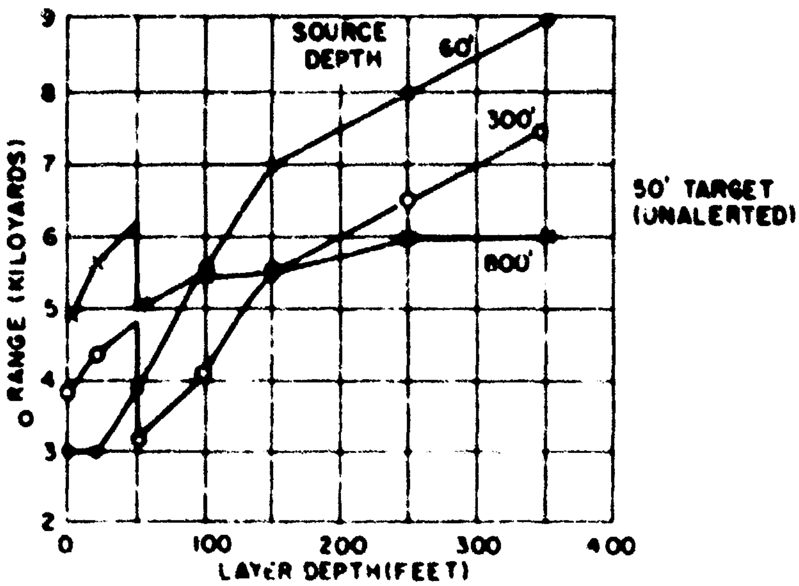


FIG 11 RANGE TO A TRANSMISSION LOSS OF 80 db VS LAYER DEPTH

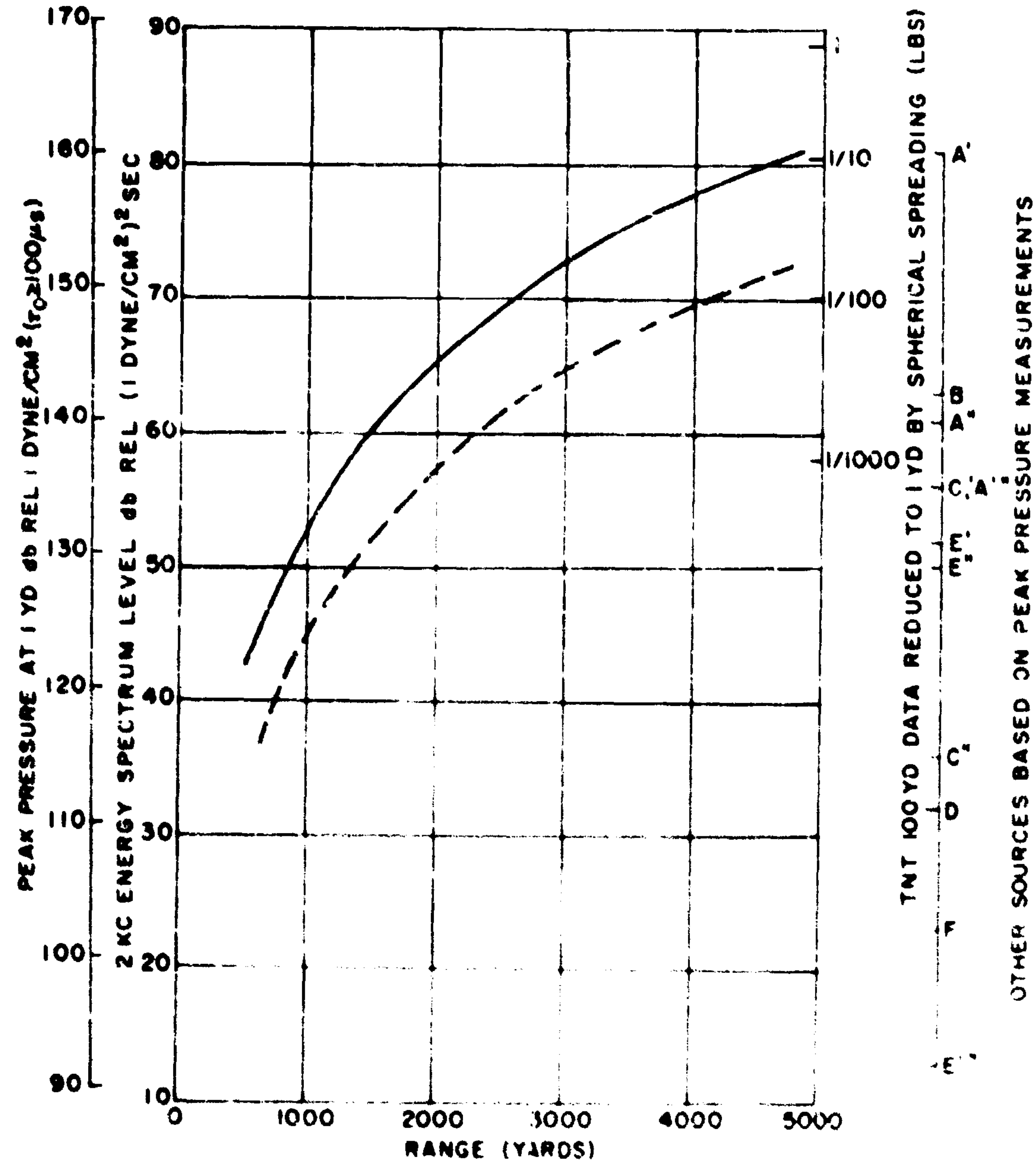


FIG 12 EXPLOSIVE SOURCE LEVELS REQUIRED FOR EER DETECTION AT 2 KC AGAINST AMBIENT NOISE UNDER GOOD SOUND TRANSMISSION CONDITIONS (SPHERICAL SPREADING)

LEGEND FOR FIGURE 12

A: Underwater Spark

A' : 1/2" gap, 750 µf, 20 kv. Reference (g)
A" : 1/2" gap, 30 µf, 15 kv. Reference (g)
A"': ---- , 60 µf, 15 kv. Reference (k)

B: Mechanical Impact Source, WHOI Mod 1. Reference (g)

C: Exploding Bridge Wire (EBW). Reference (g)

C' : 6" length, 25 µf, 10 kv
C" : 1/4" length, 12 µf, 2.8 kv

D: Pneumatic Sound Source. References (h) and (k)

E: Hydrogen - Oxygen Explodex

E' : Volume: 2 liters, Reference (i)
E" : Volume: 3.6 liters, References (i) and (j)
E"': Volume: 0.1 liter, Reference (m)

F: Propex Explosive Noisemaker (Propane and oxygen mixture)
References (n) and (o).

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Echo-ranging	ECHR	Depth settings	DEPH		
Sonar	SONA	Charges	CHAR		
Julie	JULI	Spectrum	SPEC		
Project	PRJE	Minimum	MINM		
Equations	EQUA	Levels	LEVE		
Transient	TRNN	Underwater	UNDE		
Sources	SOUR	Sound	ACOU		
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Echo	ECHO				
Reverberation	REVE				

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(NOL technical report 61-176)
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(U), by R.J. Urick, 30 November 1961.
42p. illus.

CONFIDENTIAL

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3. Underwater Sound - Sources

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